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(54) Abstract Title

Controlling coning by sensing a formation fluid interface

(57) A method of detecting a fluid interface (20) in a formation involves drilling a number of micro-boreholes (14, 15) away from the main production borehole (10) close to the zone containing the interface (20). Detectors (17a, 17b) are permanently implanted in the miro-boreholes (14, 15). By using transmitters (16) in the production borehole (fig. 3) or micro-boreholes (14, 15), signals (30) are sent into the formation that are responsive to the position of the interface (20). Processing of the detected signals (30) facilitates monitoring of the location of the interface (20), which allows operation of flow control devices to avoid coning or breakthrough of undesirable fluid into the borehole. The transmitters (16) may be deployed outside the casing (212, fig 3) in the production well or deployed on a wireline (316, fig 4). The transmitters (16) and detectors (17a, 17b) can consist of either seismic or electromagnetic sources and detectors and the interface (20) may be a boundary between oil and gas, a boundary between oil and water, a boundary between gas and water or a boundary between steam and oil.

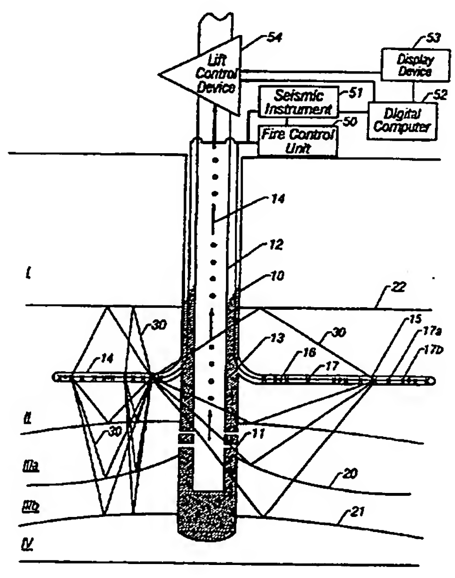

FIG. 1

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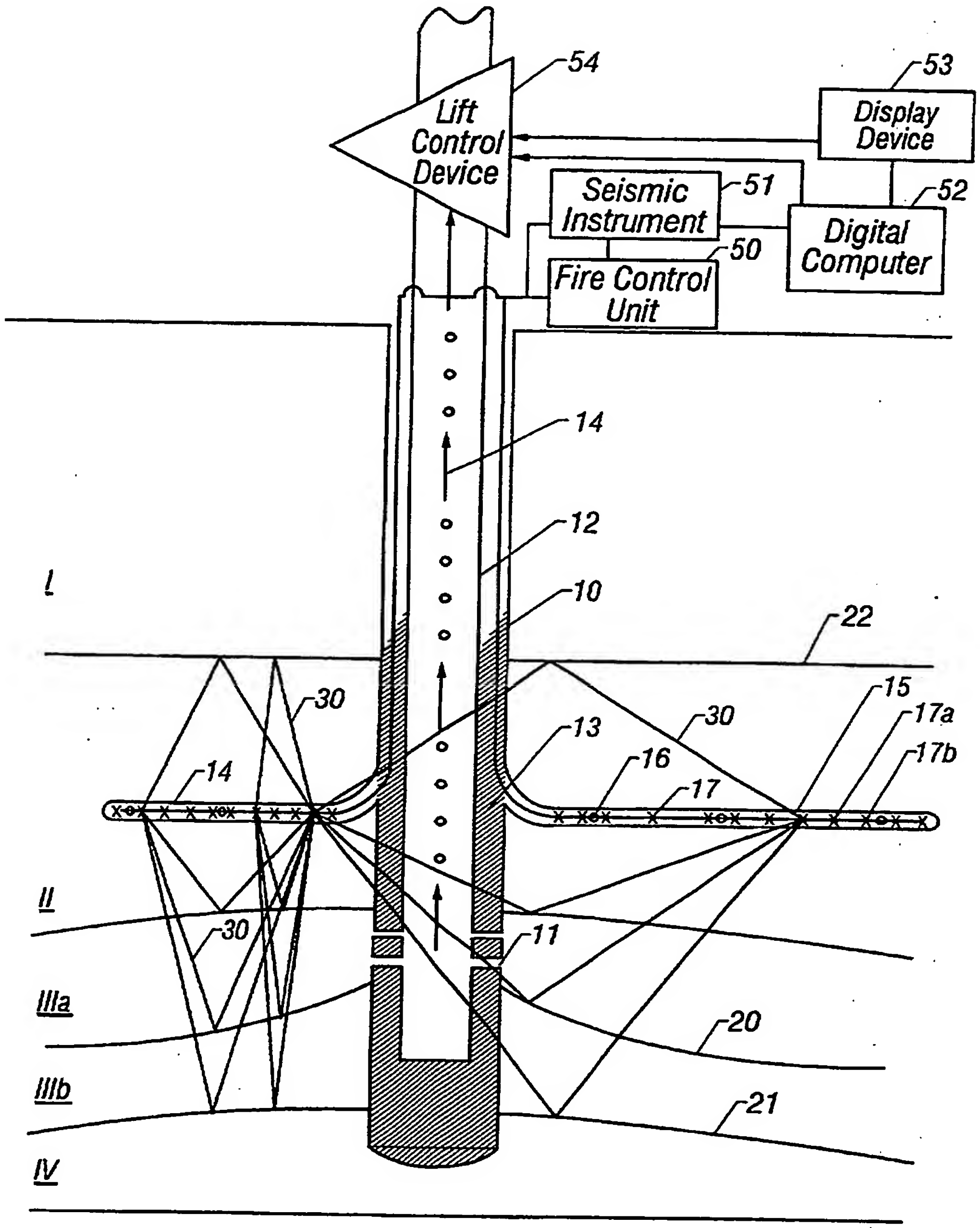

FIG. 1

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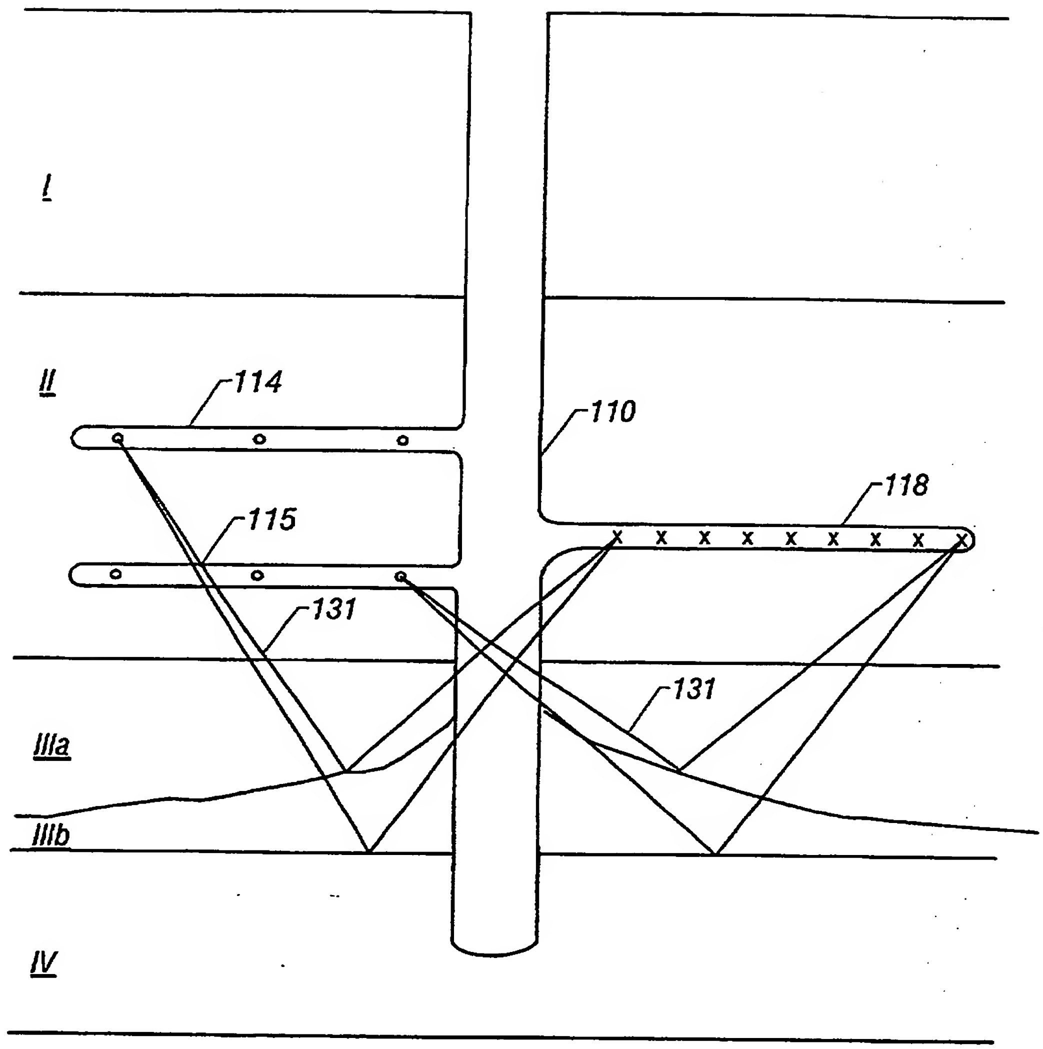

FIG. 2

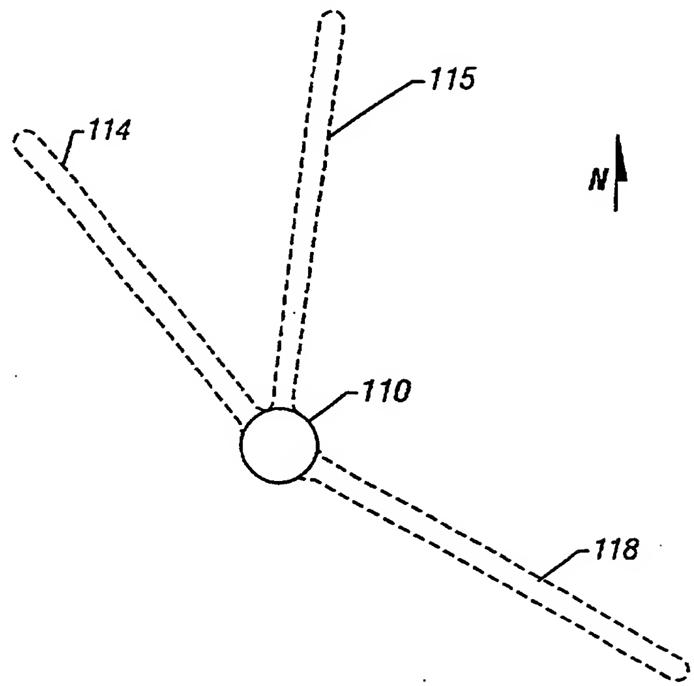

FIG. 2A

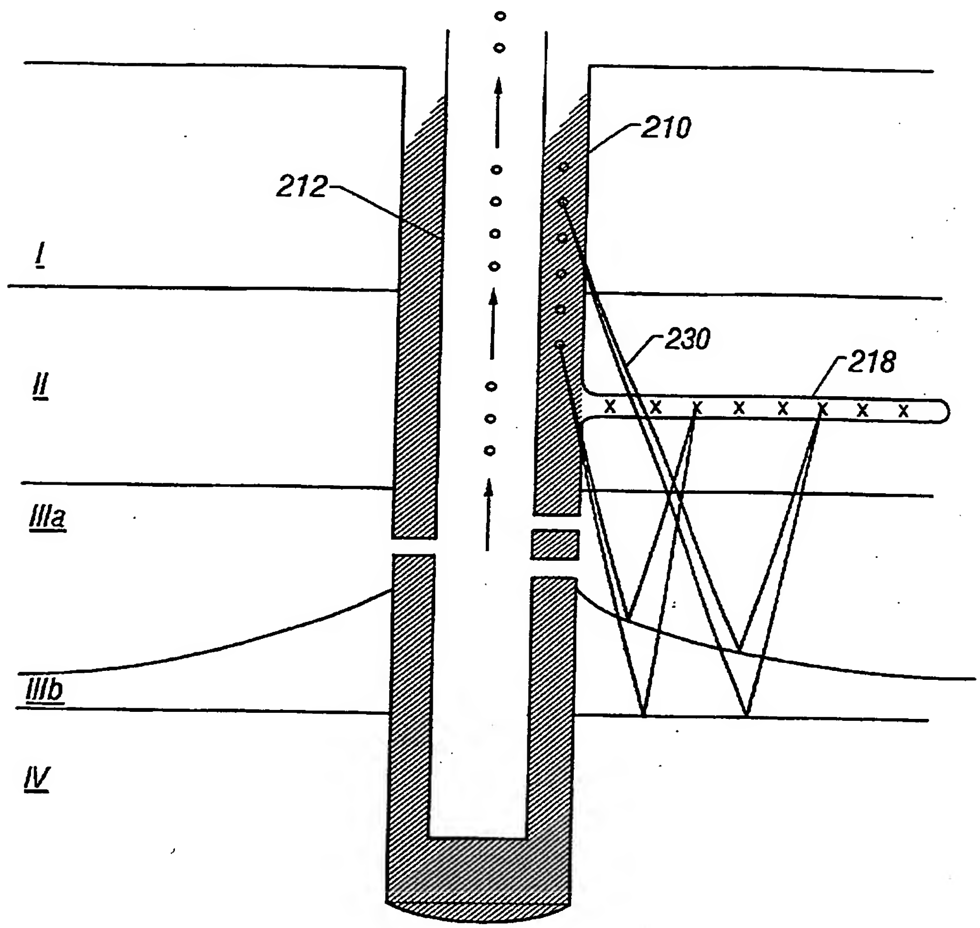

FIG. 3

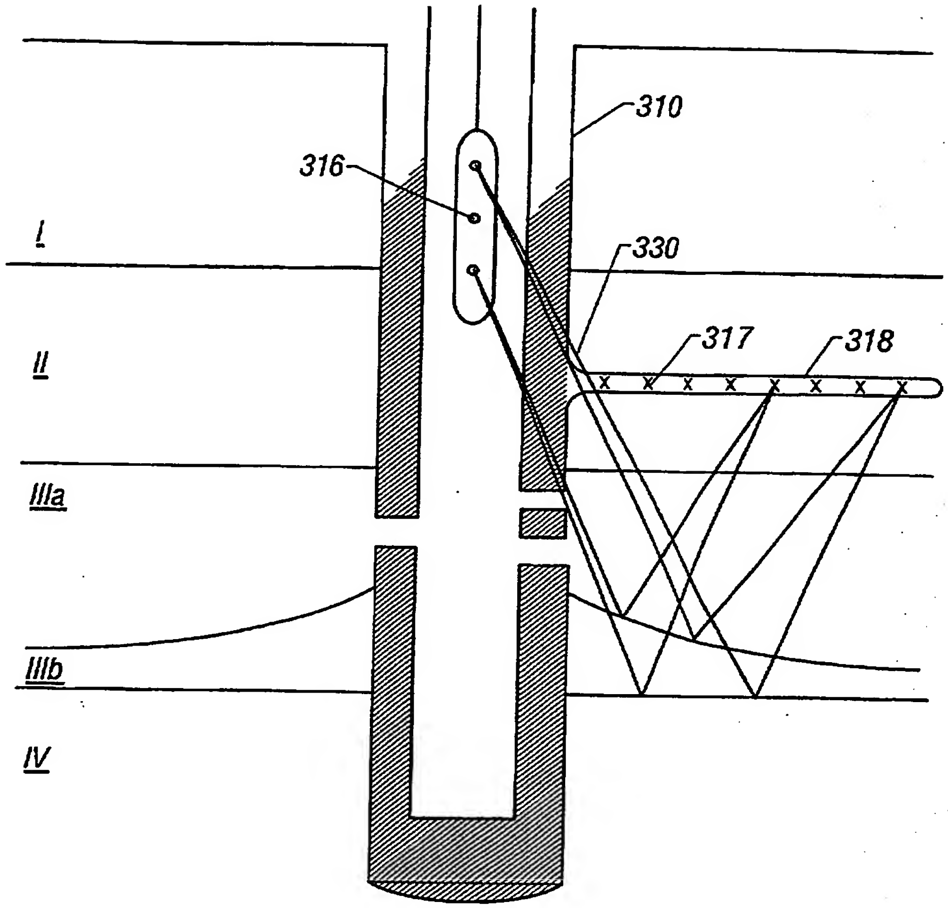

FIG. 4

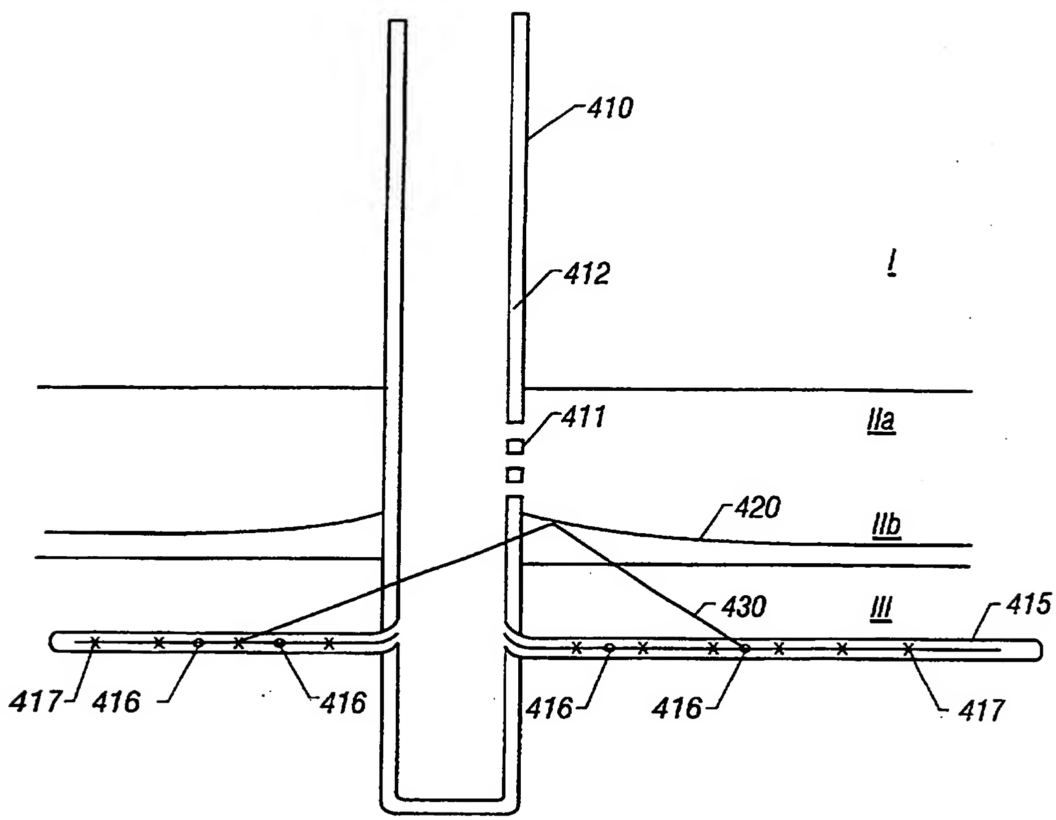

FIG. 5

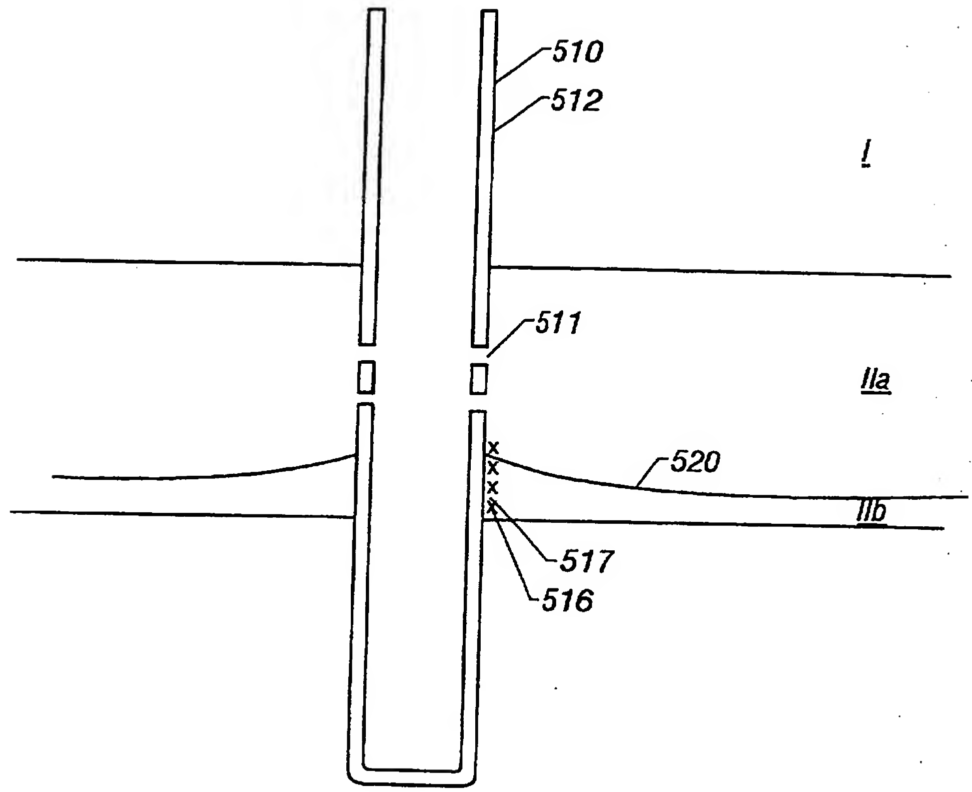

FIG. 6

METHOD AND APPARATUS FOR CONTROLLING OF CONING IN HYDROCARBON RECOVERY

The present invention relates to a method for recovering hydrocarbons from a subterranean reservoir and monitoring the oil/water or gas/water interface to avoid the breakthrough of water into a producing well. A pilot borehole is drilled from the main producing borehole and by using a combination of seismic sources and/or receivers in the pilot hole, the interface between two fluid phases can be monitored in real time.

A specific problem frequently encountered during the recovery of liquid hydrocarbons from a producing zone of a subterranean reservoir having an overlying gas cap is a phenomenon termed "gas coning". This phenomenon occurs when there is fluid communication between the producing zone and the gas cap across vertical flowpaths. The producing wellbore is provided with flow control devices that are maintained in a closed position within the gas and are open in the oil. Under sufficient drawdown pressure, the high mobility gas cap gas is drawn down from the gas cap through the vertical flowpaths into the producing zone where it commingles with the lower mobility liquid hydrocarbons residing therein.

Once in the producing zone, the gas cap gas tends to inhibit the flow of liquid hydrocarbons into the wellbore by preferentially flowing through the producing zone and entering the wellbore to the exclusion of the liquid hydrocarbons. Accordingly, gas coning is characterized by a significant increase

in the gas/oil ratio of the produced fluids and an attendant significant decrease in the liquid hydrocarbon recovery rate from the production wellbore.

A similar problem occurs even in the absence of a gas cap when the oil is in top of water in a reservoir rock. The flow control devices in this situation are arranged to produce from the upper portion of the reservoir and to avoid the production of water. A water cone develops in the vicinity of the producing well with the narrow portion of the cone being at the top, in contrast to the case of gas coning where the narrow portion of the cone is at the bottom.

A similar problem occurs in thermal secondary recovery operations. Thermal secondary recovery operations are routinely employed to recover heavy hydrocarbons, e.g. heavy oil, from subterranean reservoirs (e.g. oil sands). Due to its high viscosity, the heavy oil must be heated in place to reduce its viscosity so it will flow from the reservoir. Probably the most common of such thermal recovery operations involves "steam stimulation" wherein the heavy oil is heated in place by steam which is injected into the reservoir. A steam stimulation or steamflood process can be carried out by either (a) injecting the steam into an injection well and then producing the hydrocarbons from a separate well or (b) injecting the steam and then producing the fluids through the same well. This type of steamflood operation results in a steam cone at the top of the heavy oil.

It is not uncommon for the same liquid hydrocarbon reservoir to be in contact with a bottom water zone as well as a gas cap. Consequently, quite often a liquid hydrocarbon reservoir will be sandwiched between a gas cap above and a water zone below with both the gas and water capable of playing beneficial

roles. For example, the expansion of the gas cap can be exploited to provide driving force for pushing the liquid hydrocarbons out of the underground reservoir. Similarly, if the water zone is being energized by an underground aquifer, then the energy of the aquifer and the density difference between water and hydrocarbon can be exploited to move liquid hydrocarbons out of the formation.

United States Patent No. 5,511,616 issued to *Bert* discloses a method using an "inverted" production well for recovering hydrocarbons in a steam injection process from a subterranean reservoir wherein the production wellbore has a substantially vertical, non-inverted portion with angle building to near 90^0; an integral, substantially horizontal portion which extends into said reservoir; and an integral, upwardly curving tail portion which terminates near the top of the reservoir. A string of production tubing which may include a downhole pump is positioned within the non-inverted portion of wellbore. The inverted well increases the production interval within the reservoir and reduces bottom-water coning.

United States Patent No. 5,322,125 issued to *Sydansk* discloses the use of a foamed gel containing a crosslinkable polymer, a crosslinking agent, an aqueous solvent, a surfactant, and a gas injected through the production wellbore into gas-permeable matrix between the gas cap and wellbore, thereby effectively blocking or reducing the downward flow of gas from the gas cap to the production wellbore and enabling the more desirable liquid hydrocarbons to enter the wellbore for production to the surface.

United States Patent No. 5,421,410 issued to *Irani* discloses a method wherein a polymer or a surfactant together with a cosolvent is introduced into a gaseous stream, e.g. carbon dioxide, in such ratio as to make the mixture just homogeneous when injected through the appropriate perforations into the zones above and below the oil bearing strata. The mixture is subject to destabilization thereafter, either through some exiting feature of the reservoir such as temperature or the presence of water, or through some externally implemented event, such as a sudden lowering of the pressure in the vicinity of the well bore. This causes the polymer or surfactant to come out of solution and aid in plugging the zones through which vertical movement of gas and water, i.e. coning, had been taking place.

The prior art methods require somewhat complicated technologies. In addition, the control of the coning is on an *ad hoc* basis with little regard to maintaining a high rate of production. There has been discussion in the literature suggesting that maximum production over time is attained by a process in which the well is produced rapidly until just before the cone breaks through to the producing levels in the wellbore and then slowing the rate of recovery until the cone subsides. This "on-off" method of flow control is ideally suited for typical lift and flow control devices used in conventional production technology. However, it requires the ability to monitor the level of the fluid-fluid interface defining the cone.

The typical lateral dimensions of the cone may be a few hundred meters or less, and the typical reservoir formations may be a few meters or less in

thickness. Conventional wireline methods are not suitable for detection of coning. Sonic wireline surveys do not "see" any significant distance into the formation, so that by the time a cone is detected, it may be too late. In addition, wireline surveys require that the production be shut down: this is an added expense over and above the cost of the survey itself. The use of steel casing in a typical production environment rules out the use of electromagnetic induction methods to see away from the borehole. Surface seismic surveys, while they can provide information in real time and do not require a shutdown of the well, do not provide the necessary lateral and vertical resolution. The vertical resolution of surface seismic methods for a reservoir at a typical reservoir depth of 4km. to 6 km. is of the order of a few meters or tens of meters and will not be able to easily resolve the fluid-fluid interface. The lateral resolution of surface seismic methods is of the order of tens or hundreds of meters: this makes it difficult to resolve the coning. In addition, surface seismic data is expensive to acquire.

It is desirable to have a method of monitoring the location of interfaces between two different fluids in a producing reservoir so as to be able to control production devices in the borehole and limit the production to the desirable fluid. Such a method should preferably provide information in close to real time and also have a high resolution, so that optimum production rates can be maintained without coning.

One embodiment of the present invention provides a method for emplacing instruments in micro boreholes extending from a production borehole in proximity to a hydrocarbon reservoir from which oil or gas is being produced and using them to

detect the location of the hydrocarbon/water interface near the production borehole as well as changes in its location. In one method, multiple seismic sources and receivers are permanently deployed in micro boreholes extending laterally from the production well to either side of it above or below reservoir to be produced. Electrical signals produced by the conventional receivers which may be hydrophones, geophones or accelerometers, in response to elastic waves generated by one of the sources when it is activated are transmitted to the surface through the production well, recorded on a conventional seismic instrument including an analog-to-digital converter and processed by conventional as well as novel geophysical digital processing methods to detect arrivals reflected from both stationary rock interfaces in the vicinity of the production borehole and also from the hydrocarbon/water fluid contact within the reservoir being produced which moves as production proceeds. By comparing records obtained from the same set of sources and receivers at different times during the production life of the production well, changes in the geometry of the hydrocarbon/water fluid contact within the reservoir near the production borehole are detected and used to control the flow rate in the production well to avoid or at least delay intrusion of water from beneath the hydrocarbons in the reservoir into the production borehole perforations which is known as water coning.

In another embodiment of the present invention, the sources are located in a separate lateral micro borehole from the receivers. In yet another embodiment of the present invention, the seismic sources are located in the production borehole and may be either permanently emplaced there between the

production well casing and the rock formation wall of the production well or temporarily emplaced there on a wireline device deployed through a lubricator inside the production well casing from time to time and withdrawn from the production well when a complete record comprised of a recording from each source point at each receiver location has been obtained at a given time or during a single deployment.

Another embodiment of the present invention involves the emplacement of electrical sources and sensors in the micro boreholes or of electrical sources in the production borehole and electrical sensors in the micro boreholes extending from it and detecting the proximity of the water in the reservoir to the production borehole perforations by a change in the measured rock conductivity or resistivity.

For detailed understanding of the present invention, reference be made to the following detailed description of the preferred embodiment, taken together with the accompanying drawings, in which like elements have been given like numerals, wherein:

Fig. 1 shows a schematic illustration of a production borehole and lateral micro boreholes extending from it in which acoustic sources and receivers are permanently deployed for conducting repetitive seismic according to an embodiment of the present invention.

Fig. 2 shows a schematic illustration of a production borehole lateral micro boreholes extending from it in each of which either multiple seismic sources or

multiple seismic receivers are permanently deployed for conducting repetitive seismic surveys according to an embodiment of the present invention.

Fig. 2a shows a plan view of the schematic illustration depicted in Fig. 2 with placement of different lateral micro boreholes at different azimuths.

Fig. 3 shows a schematic illustration of a production borehole which multiple seismic sources are permanently emplaced and of one or more lateral micro boreholes extending from it in which multiple seismic receivers are permanently emplaced for conducting repetitive seismic surveys according to an embodiment of the present invention.

Fig. 4 shows a schematic illustration of a production borehole in which one or more seismic sources may be temporarily deployed and of one or more lateral micro boreholes extending from it in which multiple seismic receivers are permanently emplaced for conducting repetitive seismic surveys according to an embodiment of the present invention.

In general, embodiments of the present invention provides methods of detecting the location of a fluid interface within a hydrocarbon reservoir in the vicinity of a producing well with greater precision than it can otherwise be located by employing downhole sources and detectors in lateral boreholes near the producing reservoir extending from the producing well. It also provides methods for using the image of such a fluid interface, the location of the interface determined from it or the change in location of the interface determined from a succession of such images or determinations to control the fluid flow in the producing well.

Fig. 1 shows a schematic illustration of an example of the placement of seismic sources and receivers in deep micro boreholes for conducting subsurface seismic surveys according to one aspect of the present invention. For the purposes of illustration and ease of understanding, the methods of the present invention are described by way of examples and thus, such examples shall not be construed as limitations. In particular, while the example shown is for a water cone underneath an oil-saturated zone, the same method can be used for monitoring other types of fluid interfaces described above.

In this configuration, a production borehole **10** is drilled and completed in a particular hydrocarbon reservoir interval by conventional methods based on any pre-existing information about the subsurface. Such information typically includes seismic surveys obtained with sources and receivers located at or near the surface of the earth or sea bottom and may also include information obtained from boreholes previously drilled in the vicinity of the production borehole, for example, with wireline logging devices, from full or sidewall core samples or from pressure or fluid flow tests. As an example, **Fig. 1** shows separate rock intervals **I, II, III** and **IV** of which interval **III** contains hydrocarbons in its upper part (i.e. in interval **IIIa**) and water in its lower part (i.e. in interval IIIb) and is referred to hereinafter as the "production zone" or "reservoir." Production well **10** is completed in the upper part **IIIa** of reservoir **III** which contains hydrocarbons by means of perforations **11** connecting the production borehole inside casing **12** to the reservoir through cement **13** which typically holds the casing in place seals off the reservoir from other subsurface formations

such as **I** and **II**. Reservoir fluids **14** may then be produced through this production well by controlling the flow rate at the surface with some kind of lift control device **54** which typically may be a pump or automated control valve.

Multiple repeatable seismic sources **16** and multiple receivers **17** are permanently deployed either on a single or on separate electrical or fiber optic cables in micro boreholes such as **14** and **15** drilled laterally from production borehole **10** at a depth near but not in the production zone.

Though not necessary, it is preferable that individual receivers such as **17a** and **17b** among multiple receivers **17** deployed in any particular lateral micro borehole such as **15** be equally spaced in a linear array with a separation between consecutive detectors small enough so that the difference in arrival time at any two consecutive receivers or detectors such as **17a** and **17b** for any reflected signal of interest is less than one half the period of the highest useful frequency in the elastic wave impulse generated by any of the multiple sources **16**. Each individual receiver or detector such as **17a** or **17b** may also itself be composed of an array of several separate detecting elements extending along the axis of micro borehole **15** and the electrical signals from each of these detecting elements summed and recorded as a single signal corresponding to the position of the center of this array. This geometry is a well-known method for suppressing high energy tube waves which may be generated by sources **16** and can propagate along micro borehole **15** if it is left open (i.e. if it is only fluid-filled) and which can interfere with detection of the desired reflection signals. Alternatively, since both sources **16** and receivers **17** are permanently

deployed in micro boreholes such as **14** and **15**, such micro boreholes may be filled with cement or some other solid substance following deployment of sources **16** and receivers **17** either before or during cementing of production borehole casing **12**.

While production borehole **10** must be large (i.e. usually six inches (6") or more in inside diameter) to allow a substantial flow of reservoir fluids to the surface, lateral micro boreholes such as **14** and **15** need not be large since they only accommodate sources, detectors and the cables to which they are connected. Conventional high frequency geophones with dimensions of one inch (1") or less are readily available and repeatable sources of similar dimension have been designed and are in use in commercially available slim-line wireline logging tools. Conventional piezo-electric hydrophones of much smaller dimensions are also presently commercially available as are optical hydrophones suitable for use with a fiber optic cable without transduction from a voltage to an optical signal.

Seismic waves **30** generated by any of sources **16** with electrical commands issued from fire control unit **50** at the surface of the earth which simultaneously initiate recording by seismic recording instrument **51**, are reflected from boundaries between rock layers such as **21** and **22** as well as from hydrocarbon/water contact **20** within the reservoir, detected by receivers **17** and converted to electrical or optical signals which are transmitted up through the production borehole and recorded in seismic recording instrument **51** also located at the surface of the earth near the production well head. For each separate activation of any of sources **16**, one record or seismic trace of preset

duration is recorded at each of multiple receivers **17** for the pressure or for each component of particle motion to be sensed at that receiver location in seismic recording instrument **51** and stored on magnetic tape or any other convenient digital data storage medium.

Since the reflected waves **30** to be imaged in this invention need not travel through more than several tens of meters of sedimentary rock, **16** may be very low energy devices relative to those commonly employed seismic surveying of deeply buried rocks such as those in the reservoir and thus need not cause any damage to production borehole **10** or the bond between production borehole casing **12** and the surrounding rocks in intervals **I, II, III** or **IV** provided by cement **13**. Furthermore, seismic sources **16** generate either predominantly compressional waves or predominantly shear waves of a specific polarization or both.

Seismic receivers **16** may include devices such as geophones or accelerometers capable of detecting the amplitude of a particular component of particle motion or devices such as hydrophones which sense the magnitude of the pressure resulting from the passage of any elastic wave.

Stored seismic traces may be read into digital computer **52** and processed with a sequence of conventional seismic processing computer programs to enhance reflection signals **30**, suppress noise and other types of coherent signals and form an image of hydrocarbon/water interface **20** as well as reflecting interfaces between different rock intervals such as **21** and **22**. If the propagation velocity in the various rock intervals is provided or estimated for the type of

reflected elastic wave detected, such an image reveals the location of hydrocarbon/water interface **20** near production borehole **10** with respect to the other reflecting interfaces such as **21** and **22** as well as with respect to the known positions of sources **16** and receivers **17** at the time the seismic traces were acquired. Alternatively, estimates of the appropriate propagation velocity in the rock intervals of interest can be derived from the acquired seismic data themselves using known methods and the necessary image of the reflecting horizons can be formed using this estimated velocity. Such methods for the determination of propagation velocities would be known to those versed in the art. An image produced in this fashion may then be displayed using display device **53** which may be a camera, plotter, cathode ray tube or any other suitable device. The location of hydrocarbon/water interface **20** may then be interpreted either with software or by inspection of the displayed seismic image and provided to lift control unit **54** to reduce or increase of hydrocarbon/water interface **20** determined from the current seismic image may be compared with that determined from a previous seismic image acquired with the same or nearly the same sources and detectors and resulting from processing with the same or substantially similar software and the differential movement in the position of hydrocarbon/water interface **20** may thus be determined from the time of acquisition of the previous seismic data to that of the current seismic data and this differential may be supplied to lift control unit **54** to change the flow rate of reservoir fluids. In case, the current image may be registered with respect to the previous image using reflection events from rock interfaces such as **21** and **22**

either above or below the producing reservoir, the positions of which do not change or change only slightly compared to that of hydrocarbon/water interface during production.

A significant feature of aspects of this invention is the ability to perform the imaging and determination of the location or change in location of hydrocarbon/water interface **20** in the vicinity of production borehole **10** at the well site within no more than a few hours following completion of acquisition of a single set of seismic traces at one time. This ability permits control of the flow rate to suppress the deleterious effects of water coning within shorter time intervals than is possible with repeated surface seismic surveys..

A significant feature of this embodiment is the use of high frequencies from several hundred up to several thousand Hertz to image the reflecting interfaces within and near the producing reservoir. Use of these frequencies allows imaging of the depth of the target interfaces including hydrocarbon/water interface **20** with much higher resolution than can be achieved with lower frequency seismic surveys conducted from the surface of the earth in which the highest useful frequency rarely exceeds one hundred (100) cycles per second. In addition, it provides a much smaller Fresnel zone at the target reflectors and coupled with a much finer local spatial sampling with source and receiver positions in the vicinity of production borehole **10**, provides a more detailed indication of the lateral variation of hydrocarbon/water interface **20** than can be achieved with the more coarse spatial sampling of source and receiver locations common in surface seismic surveying. This higher resolution

imaging permits control of the fluid flow in response to much smaller changes in the location of hydrocarbon/water interface **20** than can be reliably detected on repeated surface seismic surveys.

In addition, the use of high frequencies will likely permit acquisition of a survey during production without requiring interference with or temporary interruption of production of hydrocarbons from production borehole **10** since seismic noise from surface facilities is highest at the lower frequencies in common use for surface seismic surveying but decreases markedly at higher frequencies particularly for detectors separated from these large multiple potential noise sources by a thick interval of absorbing material such as rock intervals **I** and **II** since the absorption of seismic energy increases with increasing frequency in these materials.

Fig. 2 shows a schematic illustration of another example of the placement of seismic sources and receivers in deep micro boreholes for conducting subsurface seismic surveys according to a second method of one embodiment of the invention. In this configuration, lateral micro boreholes **114, 115** and **118** are drilled from production borehole **110** as described above in reference to **Fig. 1** and seismic sources as described above in reference to **Fig. 1** are permanently emplaced in one or more separate micro boreholes such as **118.** Micro borehole **114** and **115** which contain these repeatable seismic sources may be drilled at different azimuths from micro borehole **118** which contains permanently emplaced seismic detectors as depicted in the schematic plan view illustration shown in **Fig. 2a.** Seismic traces including reflection signals corresponding to

raypaths **130** and **131** are then recorded, processed and used to image reflecting interfaces near and within the producing zone in the manner described above in reference to **Fig. 1.** These images may then be used to control the fluid flow in production borehole **110** in the manner described above in reference to **Fig. 1.** A special benefit of this configuration is that high energy tube waves which may be generated by the seismic sources in micro boreholes **114** and **115** and which may propagate along those boreholes are not present and do not propagate in micro borehole **118** and therefore do not interfere with detection and imaging of the desired reflection events corresponding to raypaths **130** and **131** observed on the receivers in micro borehole **118.**

Fig. 3 shows a schematic illustration of yet another example of the placement of seismic sources and receivers in deep micro boreholes for conducting subsurface seismic surveys according to a third method of one embodiment of the invention. In this configuration, seismic sources are permanently emplaced in the annulus of production borehole **210** between casing **212** and the rock formations forming the walls of production borehole **210.** Seismic receivers are permanently emplaced in one or more separate micro boreholes such as **218.** Seismic traces including reflection signals corresponding to raypaths **230** are then recorded, processed and used to image described above in reference to **Fig. 1.** In this configuration, tube waves generated by seismic sources **216** in production borehole **210** are not well coupled into and thus do not propagate in lateral micro boreholes such as **218** and therefore do not interfere

with detection and imaging of the desired reflection events corresponding to raypaths **230** observed on the receivers in micro borehole **218**.

Fig. 4 shows a schematic illustration of still another example of the placement of seismic sources and receivers in deep micro boreholes for conducting subsurface seismic surveys according to another embodiment of the invention. In this configuration, hydrocarbon production from production borehole **310** is temporarily halted while repeatable seismic sources **316** are deployed on a wireline through a lubricator inside the casing in production borehole **310**. Seismic receivers are permanently emplaced in one or more separate micro boreholes such as **318**. Seismic traces including reflection signals corresponding to raypaths **330** are then recorded, processed and used to image reflecting interfaces near and within the producing zone in the manner described above in reference to **Fig. 1**.

Following excitation of seismic sources **316** at one position in production borehole **310** and recording of seismic traces containing reflection events corresponding to raypaths **330** on receivers **317**, sources **316** may be moved up or down in production borehole **310** and a new set of seismic data recorded in a similar fashion. When seismic data have been collected from the desired number of source locations within production borehole **310** during one deployment, the seismic sources are withdrawn from production borehole **310** and hydrocarbon production is resumed. While in this configuration, production must be interrupted while sources **316** are deployed and seismic survey data are recorded,

the permanent deployment of expensive seismic sources in a hostile environment is avoided.

In all of the embodiments discussed above, the position of the fluid interface may be determined with respect to the surface of the earth or with reference to a rock interface, such as **22 in Fig. 1,** or the boundary between rock formations such as **II** and **III** (where **III** comprises **IIIa** and **IIIb**).

In another embodiment of the present invention, instead of using specially drilled micro boreholes, the sensors are placed in existing wellbores that are part of a multilateral wellbore. The geometry of the data acquisition geometry for monitoring of interfaces between two fluids is similar to that discussed above with reference with to **Figs. 1 - 4** and this particular embodiment of the invention is not discussed further. In yet another embodiment of the invention shown in **Fig. 5**, the survey borehole is located underneath the producing zone. Shown is a portion of a production borehole **410** with a casing **412** having perforations **411** for producing hydrocarbons from a formation **II** that includes oil in the region **IIa** and water in the region **IIb. A** plurality of survey wellbores **415** that is beneath the producing interval are used to monitor the position of the interface **420** between hydrocarbons and water. The survey wellbores have seismic sources **416** and seismic receivers **417**. An exemplary raypath **430** of seismic energy from a transmitter to a receiver that is reflected from the fluid-fluid interface **420** is shown. The traveltime of this raypath is indicative of the position of the interface **420** and is used to monitor

the position of the interface in a manner similar to that discussed above with reference to **Figs. 1 - 4.**

Those versed in the art would recognize that instead of seismic sources, any other source-receiver type that is capable of detecting changes in the a formation within a few tens of meters of the survey holes could also be used. For example, wireline applications, induction logging sensors have been used to determine the conductivity of formations in the vicinity of a borehole. Alternatively, ground penetrating radar could also be used to map the location of the fluid interface. These variations of the present invention are intended to be within the scope of the claimed invention.

Another embodiment of the invention for monitoring the position of the interface is shown in **Fig. 6**. A production borehole **510** produces hydrocarbons from perforations **511** in a casing **512**. The producing zone **II** comprises an oil zone **IIa** and a water zone **IIb**. Transmitters **516** and receivers **517** are deployed at the bottom of the producing interval. During the course of production, the position of the fluid interface **520** will change. This causes changes in the sonic velocity of the formation adjacent to the borehole that may be detected by using seismic transmitters and receivers. When electromagnetic transmitters and receivers are used, the changing position of the interface changes the electrical conductivity of the formation adjacent to the borehole. These changes in the electrical properties of the formation may be detected by electromagnetic transmitters and receivers mounted on an electrically non-conducting portion of the casing (not shown). When producing liquid hydrocarbons from a reservoir

having a gas cap, as noted above, the gas cone is inverted. In such a case, the sensors are deployed in the producing borehole above the perforated zone.

The arrangement of sensors illustrated in **Fig. 6** may also be implemented using other sensors, such as pressure sensors or gravity sensors. When pressure sensors are deployed below the perforated zone, particularly when the interface **520** separates a gas layer from an oil or water layer. A change in the level of the interface will produce a change in the pressure measured in the sensors below the interface due to the difference in density between the fluids on opposite sides of the interface **520**. Similarly, a change in the level of the interface may also be detected by gravity sensors due to differences in the fluid densities.

While the foregoing disclosure is directed to the preferred embodiments of the invention, various modifications will be apparent to those skilled in the art.

CLAIMS

1. A method of detecting the location of at least one interface between two fluids within subsurface formations comprising:

(a) permanently placing a plurality of spaced apart detector at known locations in at least one survey borehole extending away from a producing well at depths near but not in a zone containing the at least one interface;

(b) using sources in proximity to the producing well and the at least one fluid interface for transmitting signals into the subsurface formations and receiving signals at said detectors indicative of the location of the at least one fluid interface in response to said transmitted signals; and

(c) processing the received signals to determine the location of the at least one fluid interface.

2. The method of claim 1 further comprising forming the at least one survey borehole.

3. The method of claim 1 wherein the at least one survey borehole is above the zone containing the at least one interface.

4. The method of claim 1 wherein the at least one survey borehole is below the zone containing the at least one interface.

5. The method of claim 1 wherein the sources and detectors are selected from the group consisting of (i) seismic sources and detectors, and, (ii) electromagnetic induction sources and detectors.

6. The method of claim 1 wherein the sources are permanently in the at least one survey hole.

7. The method of claim 1 wherein the sources are permanently deployed outside a casing in the producing well.

8. The method of claim 1 wherein the sources are temporarily deployed within the producing well on a wireline and withdrawn from it following acquisition of the data.

9. The method of claim 1 further comprising repeating steps (b) - (c) at different times and detecting a change in the location of the at least one fluid interface.

10. The method of claim 1 further comprising using the determined location of the at least one fluid interface for controlling a flow control device and controlling the flow of fluids in the producing well.

11. The method of claim 1 wherein the location of the at least one interface is determined with reference to one of (i) surface of the earth, and, (ii) a rock interface in the vicinity of the at least one interface.

12. The method of claim 1 wherein the plurality of detectors and the sources are located in the same at least one survey borehole.

13. The method of claim 1 wherein the at least one survey borehole comprises at least two survey boreholes and wherein the plurality of detectors and the sources are located in a different one of the at least two survey boreholes.

14. The method of claim 1 wherein the at least one fluid interface comprises at least two fluid interfaces.

15. The method of claim 1 wherein the at least one fluid interface is selected from the group consisting of (i) a boundary between oil and gas, (ii) a boundary between oil and water, (iii) a boundary between gas and water, and, (iv) a boundary between steam and oil.

16. A method of detecting the location of at least one interface between two fluids within subsurface formations comprising:

(a) permanently placing a plurality of spaced apart detectors at known locations in a producing well at depths near the at least one interface;

(b) using sources in proximity to the producing well and the at least one fluid interface for transmitting signals into the subsurface formations and receiving signals at said detectors indicative of the location of the at least one fluid interface in response to said transmitted signals; and

(c) processing the received signals to determine the location of the at least one fluid interface.

17. The method of claim 16 wherein the transmitters and detectors are selected from the group consisting of (i) seismic transmitters and detectors, and (ii) electromagnetic transmitters and detectors.

18. The method of claim 16 further comprising repeating steps (b) - (c) at different times and detecting a change in the location of the at least one fluid interface.

19. The method of claim 16 further comprising using the determined location of the at least one fluid interface for controlling a flow control device and controlling the flow of fluids in the producing well.

20. The method of claim 16 wherein the at least one fluid interface is selected from the group consisting of (i) a boundary between oil and gas, (ii) a boundary between oil and water, (iii) a boundary between gas and water, and, (iv) a boundary between steam and oil.

21. A method of detecting the location of at least one interface between two fluids within subsurface formations comprising:

(a) permanently placing a plurality of spaced apart sensors at known locations in a producing well at depths near the at least one interface, said sensors being indicative of density of the fluids in the subsurface proximate to the producing well; and

(b) determining from the sensor measurements the location of the at least one fluid interface.

22. The method of claim 21 wherein the sensors are selected from the group consisting of (i) pressure sensors, and (ii) gravity sensors.

23. The method of claim 22 further comprising repeating step (b) at different times and detecting a change in the location of the at least one fluid interface.

24. The method of claim 22 further comprising using the determined location of the at least one fluid interface for controlling a flow control device and controlling the flow of fluids in the producing well.

25. The method of claim 22 wherein the at least one fluid interface is selected from the group consisting of (i) a boundary between oil and gas, (ii) a boundary between oil and water, (iii) a boundary between gas and water, and, (iv) a boundary between steam and oil.

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Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK Cl (Ed.S): E1F FHU

Int Cl (Ed.7): E21B

Other: Online: EPODOC, WPI, JAPIO

Documents considered to be relevant:

Category	Identity of document and relevant passage		Relevant to claims
A	GB 2311796 A	(Wood)	-
X	WO 98/15850	(Baker Hughes) Whole document, particularly figs 3 and 4	1-25
X	US 5767680	(Schlumberger)	21

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
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